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Forecasting Development

Forecasting Research Technical Report No. 368

Estimation of Sub-Daily Rainfall Accumulations by Merging Radar and Rain Gauge Data for Near Real-Time Use

By A.L. Crossley

October 2001

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Abstract

The second report of the Rainfall Network Collaboration Project, Radar - Rain gauge Merging sub-project, considers merging radar and rain gauge data for sub-daily accumulation periods. The report determines how applicable the statistical based Kriging with External Drift (KED) and the deterministic based Recursive Filter (RF) merging schemes are to sub-daily accumulation periods.

A case study of the two methods, applied to rainfall data from October and November 2000 period in the EA-Thames region, was completed. The case study compared the two merging schemes with Nimrod Radar accumulations and Ordinary Kriging of Rain gauge data. The EA-Thames region which contains over 100 hourly reporting gauges and is covered by the Nimrod Radar field allowed two rain gauge densities (1:300km^2 and 1:600km^2) to be investigated for six accumulation periods ranging from 1 hour to 24 hours.

The gauge rainfall correlation was modelled for the statistical methods KED and OK using a spherical function for each accumulation period at each time.

The study found that the KED merging method improved on Radar accumulation rmsf by 22%, and on rms values by 27% for hourly accumulation periods. The statistical KED method was found to produce much better results than the deterministic recursive filter. The report recommended the implementation of the KED method for accumulations periods of one hour and above.

Project Introduction

The Met Office and Environment Agency (EA) Rainfall Network Collaboration Project (RCP) has been set up with the objective of creating a rain gauge network that will provide good coverage across England and Wales. The project commenced on 12th June 2000 and was set up in response to the 1998 Met Office Requirements for rainfall data (which resulted in the rainfall networks policy document (UKON5)), Environment Agency reviews into rain gauge operations, and the Investigation into the Easter Floods of 1998 (The Bye Report) (which recommended greater collaboration between the Met Office and The Environment Agency in the area of rain gauging). The main objectives of the RCP were to propose a rain gauge network design (completed July 2001 ,WS Atkins, 2001) to propose procedures of collection, quality control, archiving and exchange of rainfall data (currently under consideration), explore opportunities for collaboration in inspection and maintenance (currently under consideration) and to arrange development of software to combine radar and rain gauge readings in order to produce a visual display to provide flood forecasters with an improved decision making aid. This report is the second report pertaining to the Radar - Rain Gauge Integration sub-project of RCP with the final objective of developing software to combine radar and rain gauge readings for sub-daily accumulation periods.

From discussions of network design [Rain gauge location workshop], the preliminary report into radar and rain gauge merging [Crossley, A (2000)] and the Network Design Review, [WS Atkins 2001], it is envisaged that the rain gauge network resulting from the RCP project will contain approximately 440 gauges across England and Wales. Two EA regions, EA-Southern and EA-North West, have been identified from the rain gauge network review [WS Atkins, 2001] as containing a high number of existing telemetered gauge, and therefore being closest to being able to provide a real time rain gauge network. As a result, a real time trial of the software with take place in the these two regions when data becomes operationally available to the Met Office in October 2001. For this reason, the research and development work in the merging software and been carried out on archived data from these two regions. The first report, (RCP-1) completed in September 2001 detailed trials of different methods of rain gauge merging using Met Offices Archived 24 hour accumulations

fields. This report continues the work, looking at sub daily accumulations fields using archived sub daily rainfall fields obtained from EA-Thames and EA-Southern.

Terminology

In order to avoid confusion in interpreting the applications of this research, two terms will be adopted to differentiate between radar correction schemes and radar and gauge merging schemes:

- **Adjustment schemes:** Gauge adjustment are schemes that adjust current radar data on the basis of past comparison schemes and therefore includes a prognostic element. Examples of such schemes are, The Met Offices gauges adjustment in the Nimrod radar correction scheme [Harrison, 2000], the Adaptive Calibration Technique of Lord et al. (1995), and the Surface Fitting Technique of Moore et al (1991). These types of schemes have been referred to in other research as 'calibration schemes', 'correction schemes', 'real time adjustment schemes' and 'retrospective adjustment schemes'. In this text these types of schemes will be referred to as Adjustment schemes.

- **Merging schemes:**

  Merging schemes are only applicable to accumulated rain fall periods and merge the two different types of data (gauge and radar) for the same time period. Thus a merging scheme cannot be applied to an instantaneous real time radar image as no gauge data would be available. Merging schemes do not include a prognostic element and can therefore expect to be more accurate than Adjustment schemes summed over the same period.

Introduction

Several methods of radar and rain gauge merging are reported in the literature. These include artificial neural network (ANN) models (Matsoukas, 1999), deterministic models, surface fitting methods, and statistical models, however few report on merging on a sub-daily time scale. Little research is available into statistical techniques that have been used to correct radar data in real time (on a sub-daily scale). An exception to this is the work by Seo et al, at the National Weather Service in the USA where a kriging approach was used for real time estimation. Tested in Tulsa, Oklahoma for hourly rainfall accumulations fields they observed substantial reductions in mean square errors throughout the year. However, the synoptic conditions in the US are not comparable to the UK and little can be inferred about the UK rainfall estimation procedures from such a study.

One reason for the lack of research for sub-daily rain gauge and radar merging may be due to the increased errors associated with gauge representativeness for short time scales. Cases of small scale structure in the rainfall fields increase as accumulation time decreases, introducing significant representativeness errors into any radar-gauge comparison. This raises the question of the validity of joining the two different networks together for sub-daily time-scales. However it is thought that, in cases of large bias in the radar, improvements can be obtained [Kitchen et al. (1992)]. As this report deals with sub-daily rainfall accumulations for periods as short as one hour, both representativeness and gauge quantisation will be discussed.

RCP-1 used both a deterministic method (the Recursive Filter) and several variations on the statistical method of Kriging to merge the radar and rain gauge accumulations. It was found that the Recursive Filter method id not perform as well as the Kriging methods, although improvements on the Radar accumulations schemes were observed and the method could be implemented with fewer rain gauges. There are considerable limitations to any deterministic or surface fitting method, not least that there is limited physical basis for the fitting function used to interpolate gauge measurements to background fields. In addition no account is taken of any change in the errors of the two measurement techniques for varying meteorological circumstances. This is crucial in a highly changeable environment such as the UK. This is why the adoption of a statistical technique, where the rainfall correlation is

modelled. is thought preferable in order to reduce the errors due to changing rainfall correlation. Statistical techniques require more computational time, however RCP-1 found that Kriging with External Drift can run in just over one minute for England and Wales and this is acceptable for hourly accumulations on the current operational system.

The first RCP radar- rain gauge merging sub project report (Crossley, 2001), referred to in this document as RCP-1 was completed in September 2001 and reported on merging 24 hour accumulation fields. RCP-1 recommended the implementation of a statistical based radar – rain gauge merging technique for accumulation periods of 24hours. This study aims to determine how applicable such a merging scheme is for sub-daily accumulation periods where there are significant potential errors due the representativeness and quantisation of rain gauges.

The following report takes a case study in the Thames area and applies two methods (statistical and deterministic) of merging radar and rain gauge data and compares them with radar (Nimrod corrected)- only and gauge -only accumulations.

Method

Four rainfall accumulations estimates were compared for sub-daily rainfall accumulations. Each is summarised below, a detailed account of each of the methods is given in Crossley, (2001).

1) Nimrod Radar Accumulations (Radar)

The Nimrod Radar correction scheme incorporates a gauge adjustment scheme that uses over 50 radar - gauge comparisons to determine a constant multiplicative factor to be applied to the Radar. The total Nimrod Radar correction scheme, - which attempts to remove residual clutter and anaprop, and mitigate the impact of bright band occultation and range effects- improves the raw radar on average, for the year and for the whole UK radar network by 17%. Corrections can improve the radar by as much as 45% at long range (150-200km from the radar). Although large improvements are observed by the application of the Nimrod Radar scheme it is still thought that there is room for improvement, especially at long range from the radar. Following the application of Nimrod correction scheme to the radar rainfall field, the rainfall was accumulated to give hour totals and sums thereof.

2) Ordinary Kriging Gauge Accumulations (OK)

Ordinary Kriging is a statistical kriging method that can be applied to rain gauges to produce a gauge -only rainfall estimations. (Details given in Goovaerts (1997)). The contribution of each gauge to the estimate is determined by modelling the gauge correlation function and optimal interpolation.

3) Recursive Filter Radar-Gauge merging (RF)

Details given in Crossley, 2001. This method, already used at the Met Office in the pressure – wind analysis [Standing, 2000], is a deterministic method which incorporates a simple recursive filter and provides a spatial correction to the Nimrod - corrected radar based rain accumulations using rain gauges as ground truth measurement.

4) Kriging with External Drift Radar-Gauge merging (KED)

Kriging with external drift (KED) is similar to OK but in addition to optimally interpolating the rain gauge data using the gauge correlation function, the Nimrod - corrected radar data is related to the primary variable using a linear relationship and this relationship is used to calculate the mean at each estimation point.

Modelling the rainfall correlation

As the weather across England can vary considerably, and in order to model the rainfall correlation across a relatively homogenous area, it was decided that England would be split into eight rectangular regions. Those chosen corresponds to the UK Environment Agency regions. The case study area uses data relating to the Thames Region. In each of these regions, for each accumulation period, the covariograms/variograms (which describe the correlation) are modelled using a minimisation routine and applied in the OK and KED algorithms.

Case Study EA-Thames region

To examine the four rainfall estimation techniques for short time accumulations, rainfall data was collected over a two month period between the 1st October and 30th November. This period was particularly wet, with extensive flooding during late October. The study area chosen is the EA-Thames Region which is 180km x 125km (25200km^2) and corresponds to 36 x 28 5km x 5km Nimrod radar pixels. 15 minute Nimrod corrected radar data was accumulated to produce hourly totals (and sums thereof). The rain gauge data for this period was supplied by the Environment Agency (EA-Thames and EA-Southern) from their archived gauge data set of 120, 0.2mm, tipping bucket gauges.

Experiments were carried out for two different gauge densities, 600km^{-2} and 300km^{-2}. For the higher gauge density (300km^2) a substitution method of validation was used. In this case the total gauge set (120 gauges) was divided into three subsets of 40 gauges each. For each rainfall event, two of the three sets were used for analysis, the third as the validation set. This was then rotated, producing a total validation set of 120 gauges. For the lower gauge density (600km^{-2}) the total gauge set was divided into a validation set (of 80 gauges) and analysis set (40 gauges). The numbers are

summarised below in Table 1.01. The gauge nearest the centre of the pixel was used for validation. The total events for each accumulations period is summarised in Table 1.02 . A high density of sub daily reporting gauges exists in the EA-Thames region and therefore to mirror other EA regions a lower gauge density of 1:600km^2 was also investigated.

Table 1.01. The number of validation and merging gauges for each experimental gauge density

Gauge Density	Projected no. of merging gauges over England and Wales[1]	No of merging gauges per accumulation	No of validation gauges per run	Total number of validation gauges per accumulation period
600	250	40	80	80
300	500	80	40	120

Table 1.02 Total number of recorded events possible per accumulation period

Accumulation Period (hr)	Gauge Density	Total No of Events
1	600	1440 x 80 (115200)
1	300	1440 x 120 (172500)
2	300	720 x 120 (86400)
3	300	480 x 120 (57600)
6	300	240 x 120 (28800)
12	300	120 x 120 (14400)
24	300	60 x 120 (7200)

For verification, the analysis grid point is compared to the gauge nearest to the centre of the pixel with no interpolation undertaken. The statistics used are bias, the root mean square (rms) and the root mean square factor (rmsf) which are defined below.

$$bias = \frac{1}{N}\sum_{i=1}^{N}(truth_i - estimate_i) \qquad 1.1$$

$$rms = \left(\frac{1}{N}\sum_{i=1}^{N}(truth_i - estimate_i)^2\right)^{1/2} \qquad 1.2$$

$$rmsf = \exp\left(\frac{1}{N}\sum_{i=1}^{N}(\log(estimate_i/truth_i))^2\right)^{1/2} \qquad 1.3$$

[1] The expected total number of gauges available as a result of RCP is 440, 350 EA gauges and 90 Met Office Srew Reporting gauges. The total area of England (129720km^2) and Wales (20764km^2) brings the maximum gauge density available for merging to 1:340km^2. The Existing Met Office sub daily gauge Srew report density is 1:1600km^2.

where $truth_i$ is the verification gauge at pixel i and $estimate_i$ is the estimation value at pixel i. For statistics calculated at different rainfall thresholds an event is defined as above the threshold if either the estimate or the verification gauge value exceeds the given threshold. The bias, rms and rmsf in calculated only when both the estimate and the truth values in greater than zero. When considering categorical variables such as when considering rainfall delineation three statistical measures were used. Probability of detection (POD), false alarm rate (FAR), and the critical success index(CSI). Using the truth table below these are defined as

		Estimate	
		Yes	*No*
truth	*Yes*	*A*	*B*
	No	*C*	*D*

1.4

$$POD = \frac{A}{A+C} \qquad 1.5$$

$$FAR = \frac{C}{A+C} \qquad 1.6$$

$$CSI = \frac{A}{A+B+C} \qquad 1.7$$

Where $N = A+B+C+D$ is the number of events is the number of times both the verification gauge and the estimation has measured an event of either 'zero' or 'non zero' rainfall. Non zero rainfall is defined as when the verification gauge records rainfall exceeding 0.2mm, or where the radar sees a rainfall greater than 0.005mm. Due to the discrete nature of the rain gauge rainfall measurement there will always be errors in the rainfall measurement. This is more profound at rainfall values approaching zero. Very light rain may not be registered due to evaporation. Further errors in rain gauges are due to the less than perfect conditions in which rain gauges are sited.

Results and Discussion

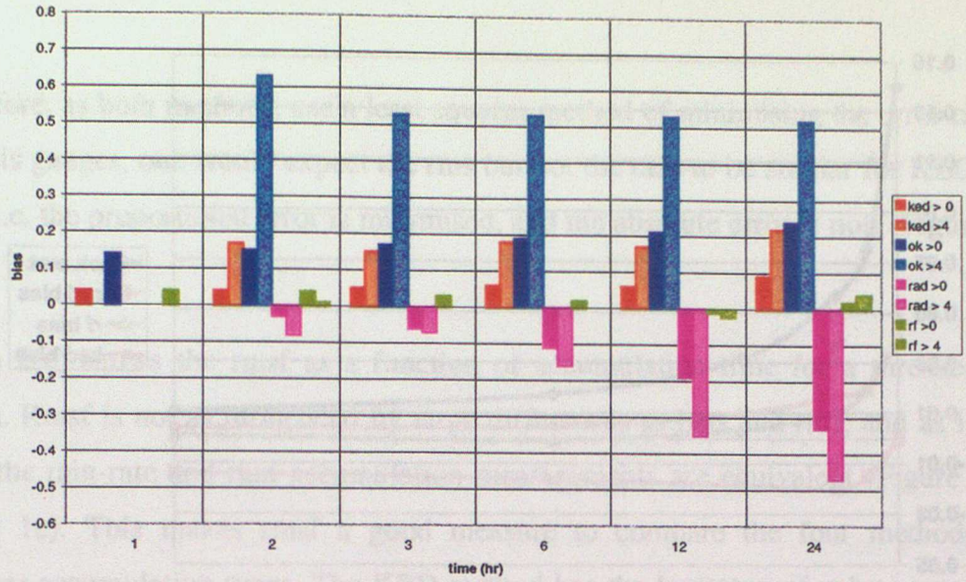
The average bias, rms and rmsf have been calculated for accumulation periods of 1,2,3,6,12 and 24hours for each of the four estimation techniques. These are displayed in Figure 1(a),(b) and (c) for two rainfall thresholds (>0mm and >4 mm).

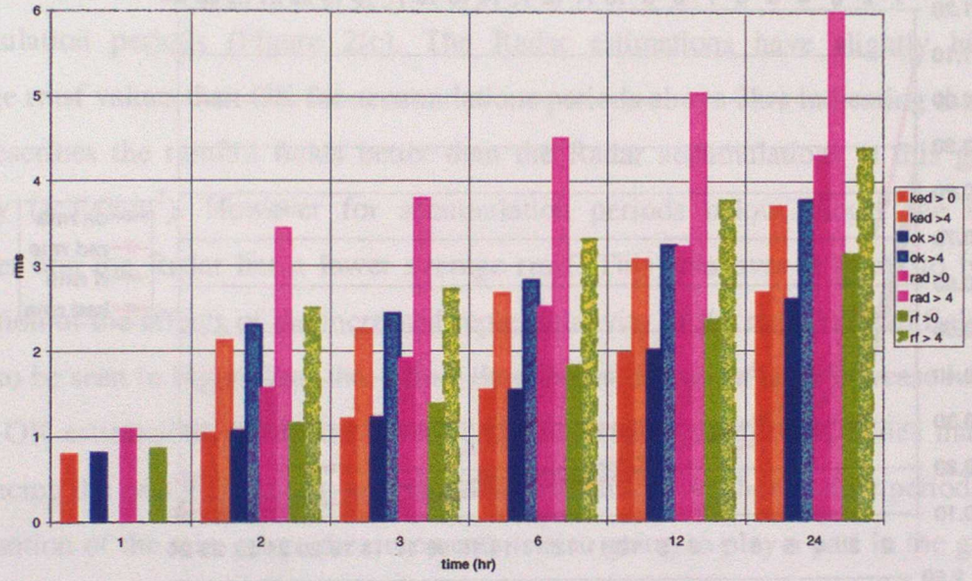
The statistics shows that the radar, in contrast to the other estimations, has, a negative bias, and is on average, overestimating the rainfall. This is in agreement with the findings of RCP-1 for 24hour accumulations in the EA-North West Region. The gauge only estimation (OK) has a positive bias, and therefore on average, underestimates the rainfall. The two merging schemes, RF and KED, both have a lower bias than the Radar and OK accumulations, except for an accumulation period of one hour, where the Radar exhibits almost zero bias. This likely to be due to the Nimrod gauge Adjustment Scheme which corrects for bias in the actual Radar fields.

Figure 2(a),(b) and (c) below, shows the bias and rms and rmsf of the rain rate (where the data has been divided by accumulation time) as a function of accumulation period for a threshold of greater than zero. All decrease as a function of increasing accumulation time.

As accumulations periods decrease, one would expect the bias to increase in estimations that involve rain-gauge data. As the period decreases, a smaller number of gauges will see any event and thus the local average will be less representative of any rainfall event. Figure 2(a) shows that the OK bias increases rapidly as accumulation time decreases, whereas the estimation methods that include radar data do not.

Similarly to the bias, the merging schemes, KED and RF, both improve on the Radar rms with KED and OK showing the smallest rms. The OK algorithm determines the extent of the influence of each rain gauge on the estimation in the same way as the KED algorithm, through modelling the gauge rainfall correlation, and minimising the errors using least squares. The difference between the two methods is that KED uses the radar to estimate the local mean field where as OK uses the surrounding gauges to estimate the mean field.





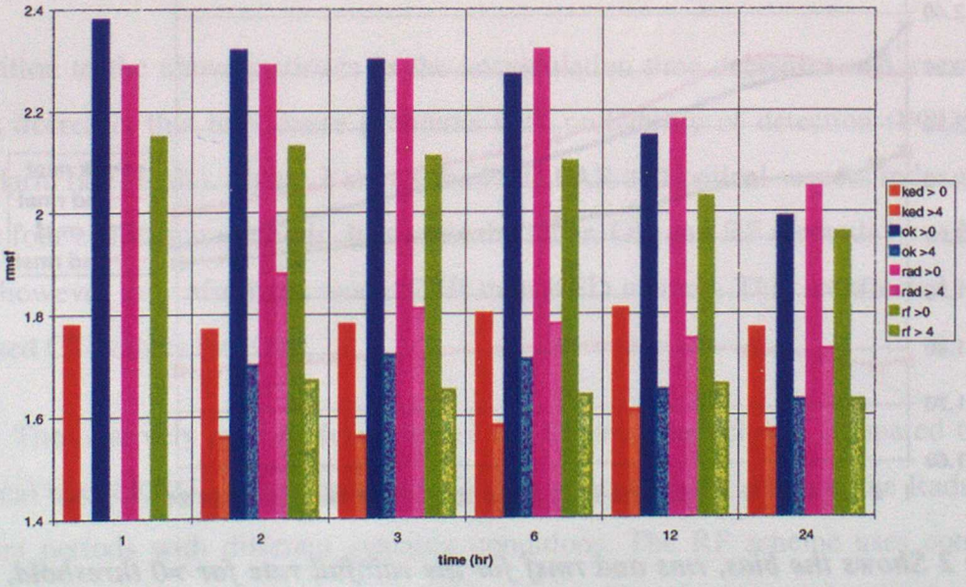


Figure 1. The bias, rms and rmsf of the four estimation techniques for different accumulation times and for two rainfall thresholds (0mm and 4mm). NB The are insufficient events to obtain statistics for a rainfall threshold of 4mm for 1 hour accumulations

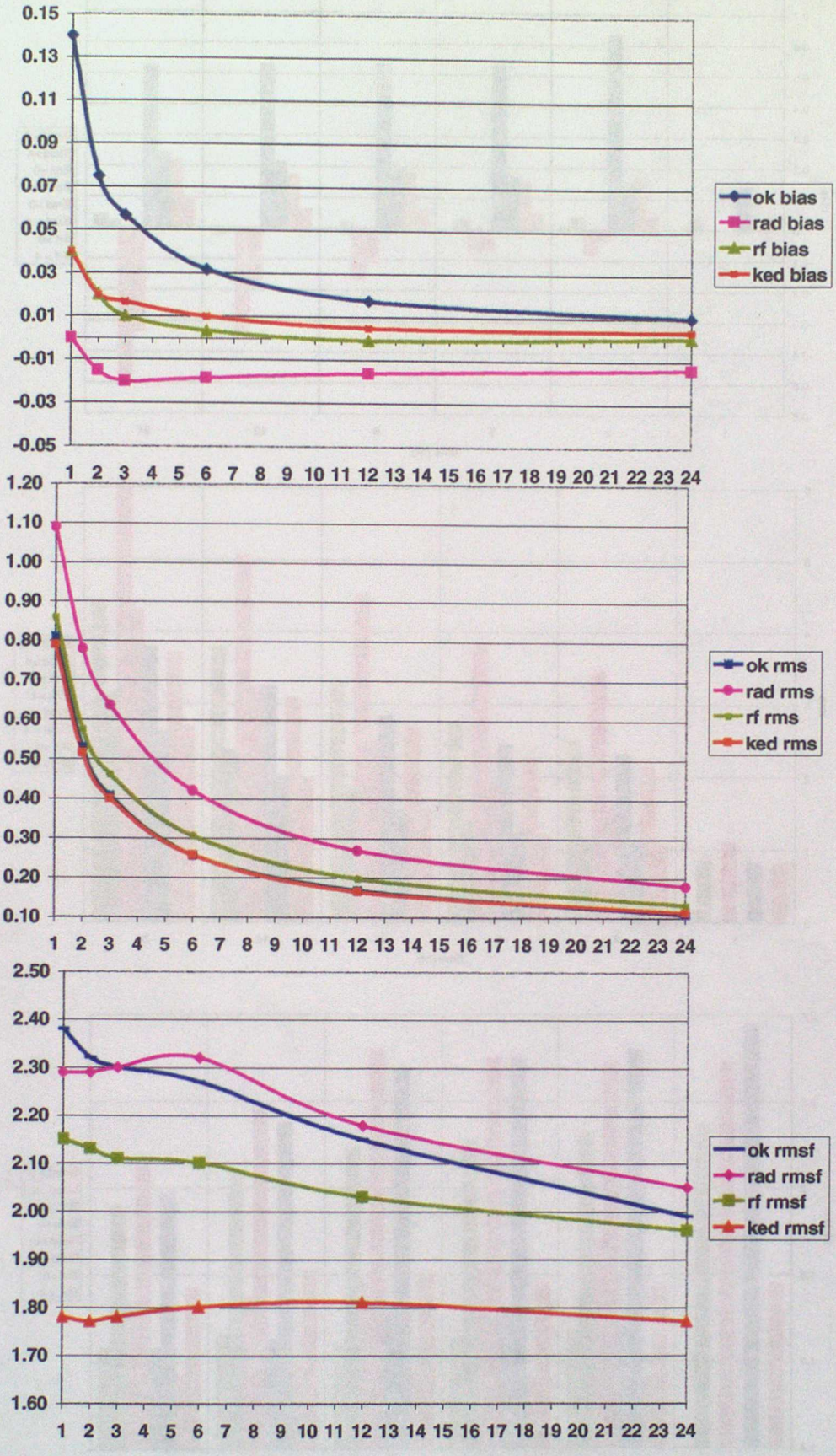


Figure 2 Shows the bias, rms and rmsf for the rainfall rate for >0 threshold, as a function of accumulation time.

Therefore, as both methods, use a least squares method of minimising the error on the analysis gauges, one would expect the rms but not the bias to be similar for KED and OK, (i.e. the proportional error is minimised, and the absolute error is not) (Figure 1a, b).

Figure 2(c) shows the rmsf as a function of accumulation time for a threshold of >0mm. Rmsf is not as influenced by large differences as bias and rms, and as it is a ratio, the rain-rate and rain accumulation measurements are equivalent (Figure 2c = Figure 1c). This makes rmsf a good measure to compare the four methods for different accumulation times. The KED method has the lowest rmsf values across all accumulation periods (Figure 2(c). The Radar estimations have slightly higher average rmsf values than OK for accumulations periods above 3hrs indicating that the OK describes the rainfall fields better than the Radar accumulations at this gauge density (1:300km^2). However for accumulation periods below 3hours the trend reverses and the Radar has a lower average rmsf. This crossover is likely to be an indication of the effects of the increased representativity of the radar rainfall fields. It can also be seen in Figure 2(a) that below three hours, there is a large increase in bias of the OK estimations. This further reinforces that representativeness issues may be influencing the ordinary kriging gauge rainfall estimation. At shorter time periods the quantisation of the rain-gauge measurements is also going to play a part in the gauge rainfall estimation errors.

In addition to the above statistics as the accumulation time decreases and averaging effects decrease, this may cause problems with probability of detection (POD) and false alarm rate (FAR). Figure 3 shows the POD,FAR and critical success index (CSI) for the four estimation methods. It is clear the radar, OK and RF methods have better POD, however they also have worse FAR than KED method. This is reflected in the increased CSI values for KED.

The relatively poor performance of the RF merging scheme compared to the statistical based KED scheme could be due the variation in the errors in the Radar for different periods with different synoptic conditions. The RF scheme uses constant parameters to define the influence of each gauge on the adjustment, whereas the KED schemes characterises the rainfall correlation for each accumulation period, thus allowing for changes due to synoptic variability.

Throughout the year and across the UK, the Nimrod accumulations for periods of one hour tend to be slightly positively biased. The Nimrod gauge adjustment has been shown to be sufficient to removing bias a short ranges, and at long range underestimation is going to happen because of detection failures. This suggests that is may be possible that large variable errors are occurring, possibly due to anaprop, in what may possibly be a small number of images. To determine whether the merging technique consistently improved the radar accumulations or whether large improvement occur in a small number of images in is necessary to break down the statistics on daily basis. Figure 4 shows a time series of the 60 minute accumulations of bias, rms and rmsf averaged over a each day of the two month period. The 24 hour periods which were dominated by convective events are indicated with a "*".

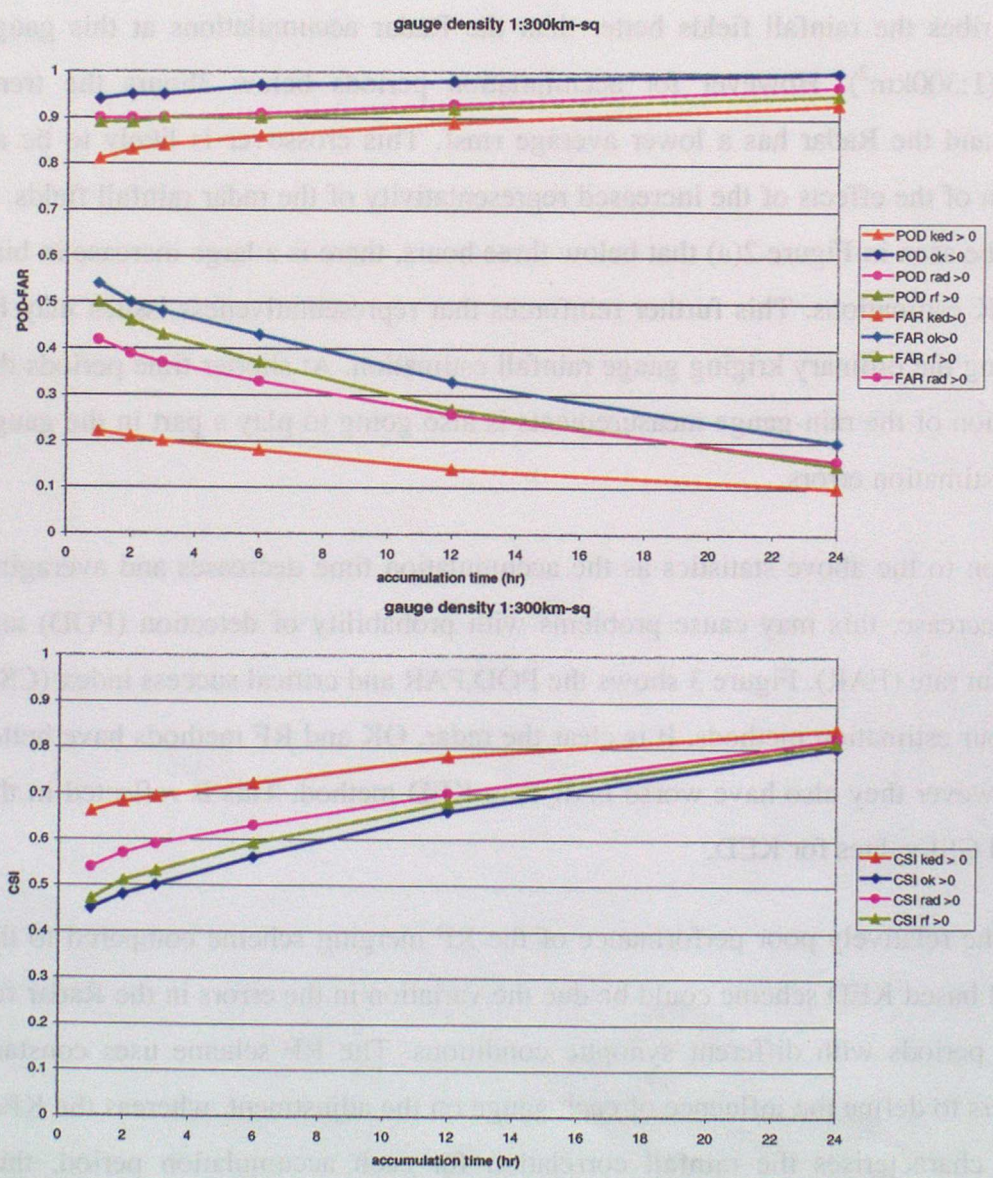
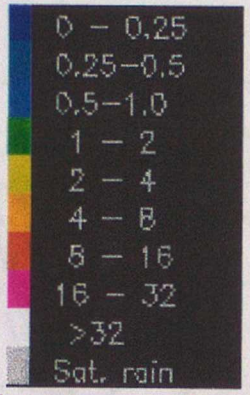


Figure 3. The POD, FAR and CSI for each of the four estimation procedures for different accumulation periods



All of the following colours in the accumulation pictures correspond to the values in this key

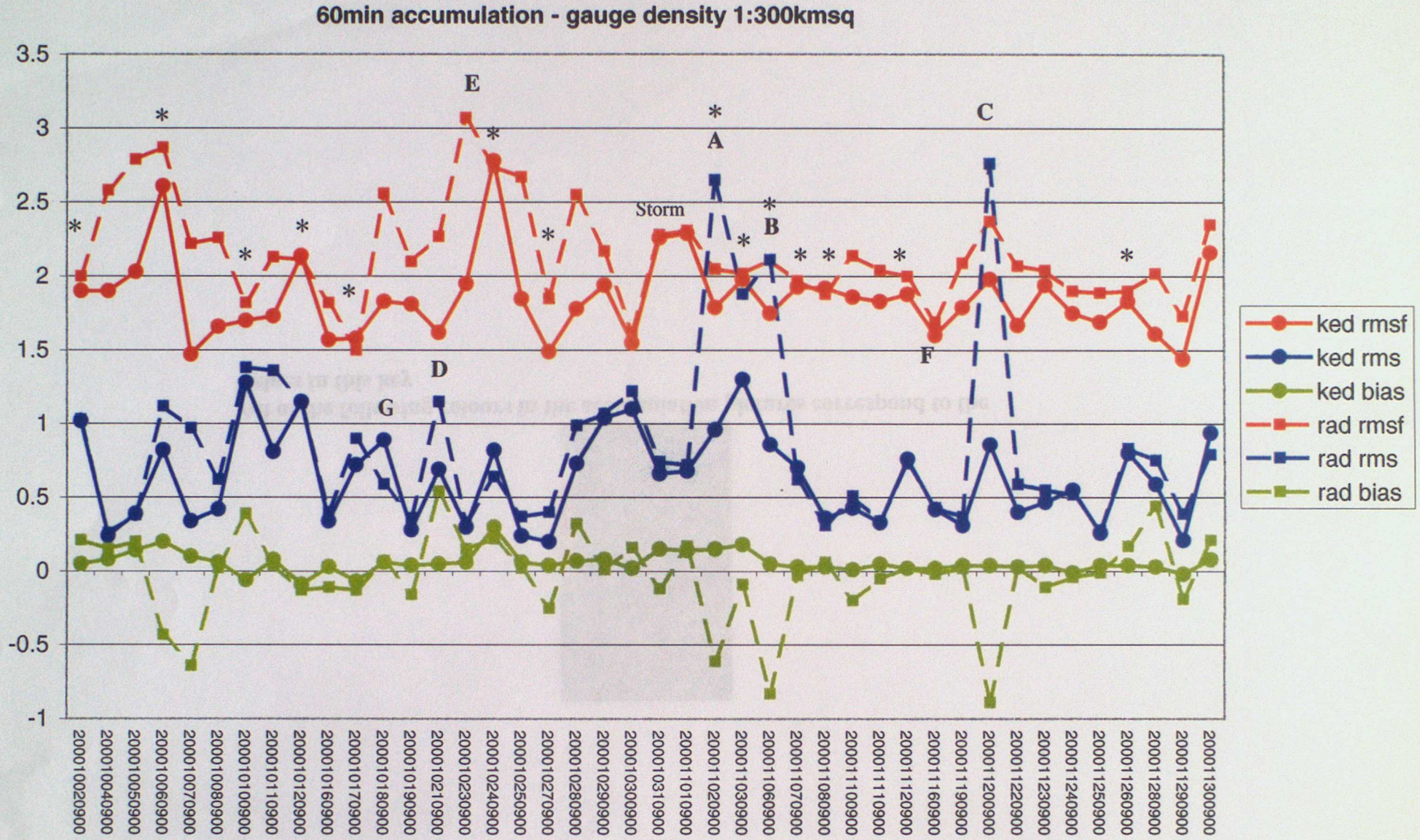


Figure 4. Time series of rms, rmsf and bias for Radar and KED 60 minute accumulations averaged over 24 hours
**=convective dominated 24 hour period as inferred from the Met Office Daily Weather Summary.*

Figure 5. Sequence of Events 200011020700 - 20001102100 Corresponding to point 4 on Figure 4 The X marks the centre of the Chenies Radar

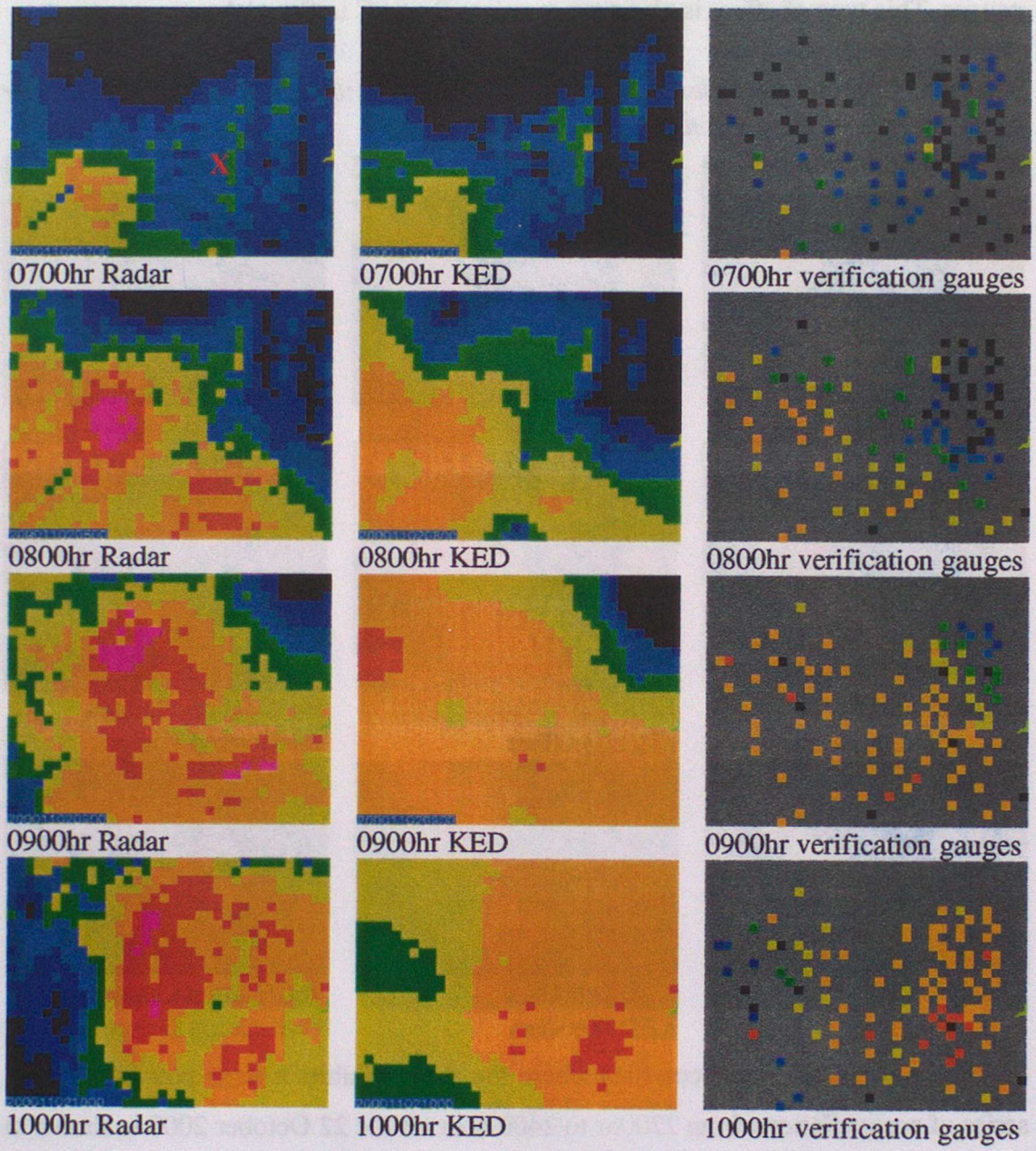


Figure 4 shows that in the two month period there were eight points where the radar exhibited a large negative bias. In six of these cases the corresponding rms values were above average. On further examination of the rainfall maps these cases were characterised by heavy rainfall. The rainfall maps for a four hour period, corresponding to point A (Figure 4), is are shown in Figure 5. The heavy rainfall combined with the date of November could have given rise to a radar bright band

effect, and this is evident in Figure 5 which shows the characteristic ring centred on the radar which develops in time. It is clear that the bright band effect has not been sufficiently compensated for in the Nimrod corrections procedures. The KED merging has compensated for the overestimation producing an image reflects the verification gauges. This type of effect is also seen at points B and C in figure 4.

Figure 6. Hourly accumulations for period between 22:00 and 00:00 on 22 October 2000, corresponding to point D on Figure 4.

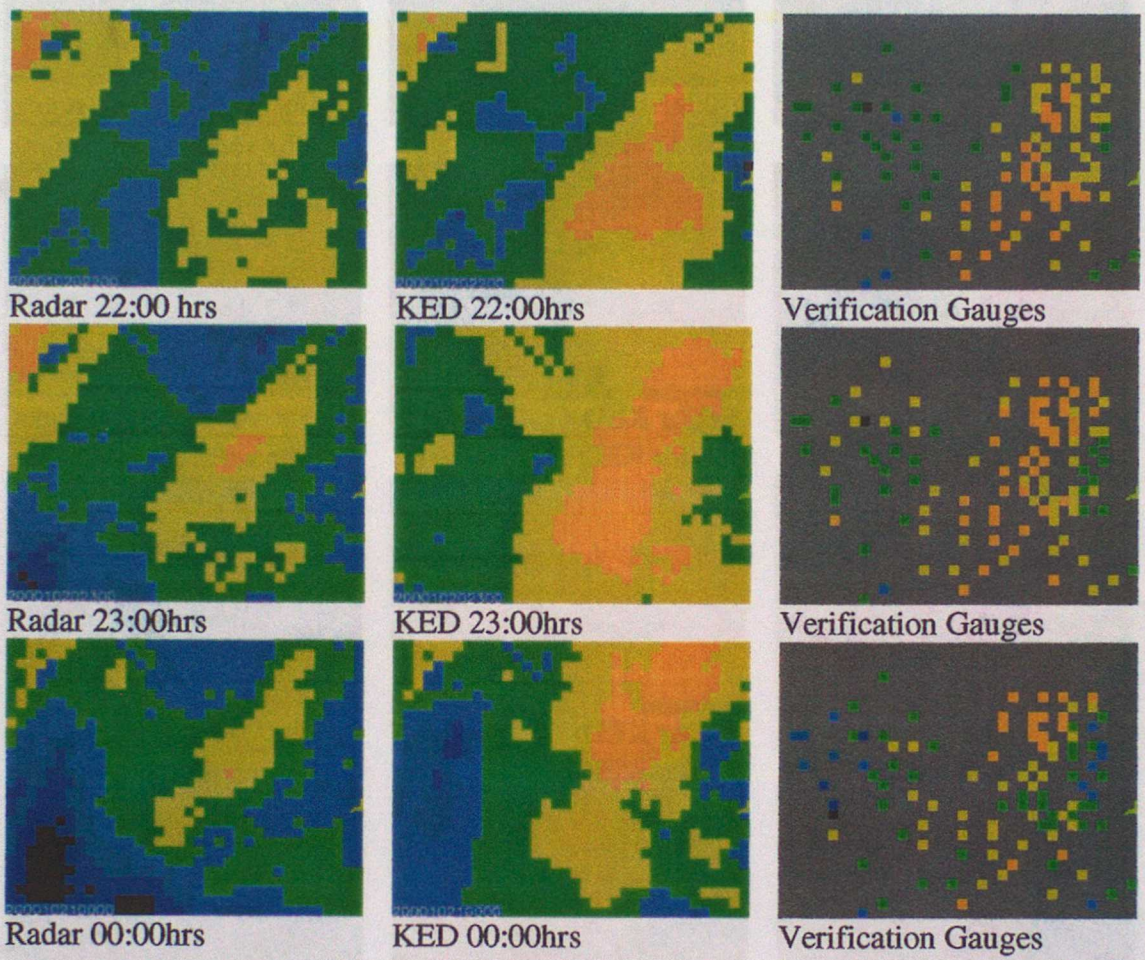
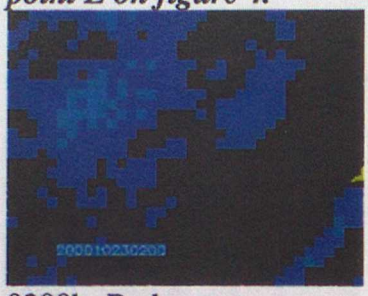


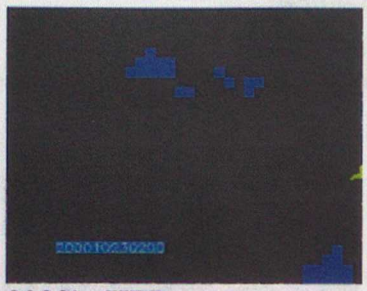
Figure 4 also shows four occasions where the radar exhibits a large positive bias. A series of accumulations from 2200hr to 2400 hour on the 22 October 2000 is shown in Figure 6. This is typical of what is seen on these occasion of large positive bias, where significant rainfall has been missed by the radar. Figure 4 also shows cases where the rmsf values of the radar accumulation are much higher than mean values (and the KED analysis). In these examples the rms and bias coincide with the KED analysis and are not above average. Figure 7 shows the rainfall maps for a characteristic hourly accumulation in these cases. All are characterised by very low rainfall. The low rainfall that is picked up by the radar, but not by the verification or test gauges. It is

likely that the increased rmsf values of the radar is due to the quantisation effects of both the verification and the analysis gauges.

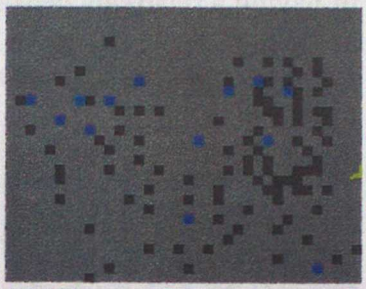
Figure 7. Light rainfall events; accumulation of 200010230200. Corresponding to point E on figure 4.



0200hr Radar



0200hr KED



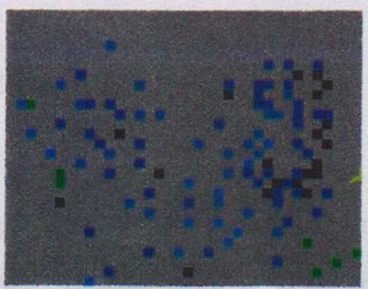
0200hr verification gauge

Figure 4 to 7 show that a relatively small number of events have negatively influenced the radar statistics. There are four events (of those described by Figure 5) where the bias is negative and large. If these were excluded, the rms would be similar to that of the average KED value of 0.8, compared to the radar actual average rms value of 1.0. The seven events where the radar have clearly underestimated the rainfall The underestimation in rainfall by the radar which has also occurred for 7 events, is less easily explained. The benefits of having a spatial correction are clearly observed in both cases of large bias and this has been observed by other authors notably for the Paris radar by Creutin (1988). If in the cases of low bias and rms, the high values of rmsf can be attributed to quantisation effect of the rain gauge, the average value of the rmsf of the radar would be lower. Indeed there are several days where the radar rmsf is coincident with the KED rmsf, -an example corresponding to point F on Figure 4 is shown in Figure 8 - at values of just over 1.5. This is consistent with the value of rmsf given by Kitchen et al (1992) corresponding to the limit of the resolution of the radar due to representativeness errors.

Figure 8 Hourly accumulation to of 15th Nov 23:00, corresponding to point F in figure 4

Radar 23:00hrs

KED 23:00 hours



Verification Gauges

Point G in Figure 4 illustrates a point where the radar has performed better in rms than the KED analysis. Figure 9 illustrates a typical accumulation from this period. In this case it is likely that, due to the scattered nature of the showers, that the merging gauges have not picked up some heavy showers. This example shows the importance of having a relatively dense network.

Figure 9. Hourly Accumulation of 200010180300. Corresponding to point G on figure 4.

Radar 03:00 Hrs KED 03:00hrs Verification Gauges

To determine how effective the KED estimation technique was compared to the radar accumulations on a individual point by point basis, Figure 10 shows a scatter plot of the error (ε = estimation - verification gauge) of the radar and KED estimations. The scatter plot shows a bias towards higher errors in the radar.

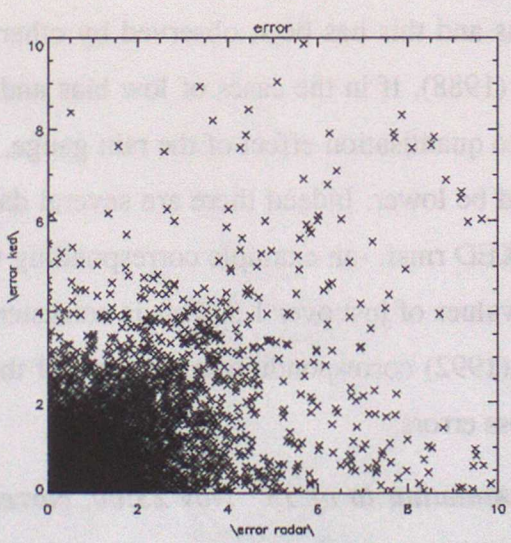


Figure 10. Scatter plot of radar error and KED error

Analysing the errors it was found that for all errors KED merging had lower errors than the radar 91% of the time. If errors of less than 0.3mm were excluded, KED had smaller errors 72% of the time. The radar and KED errors are displayed as a

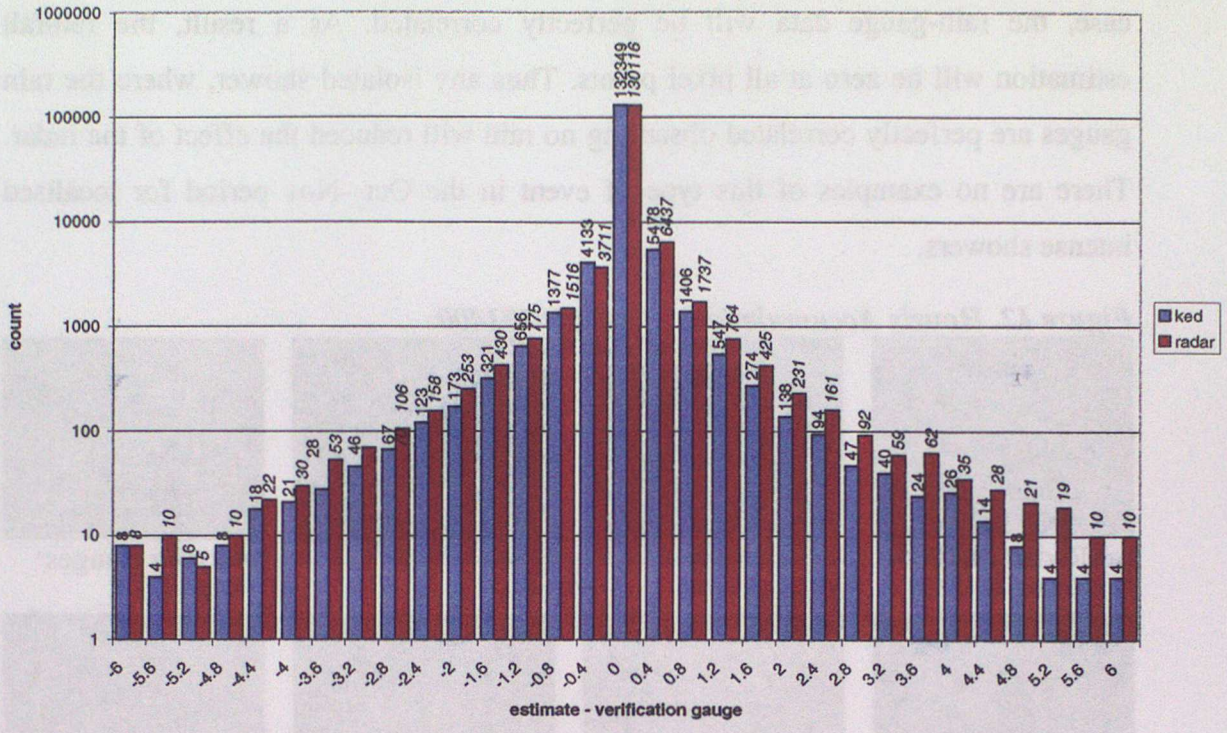


Figure 11 Histogram of the Differences in error of the Radar and KED (estimation - verification gauge)

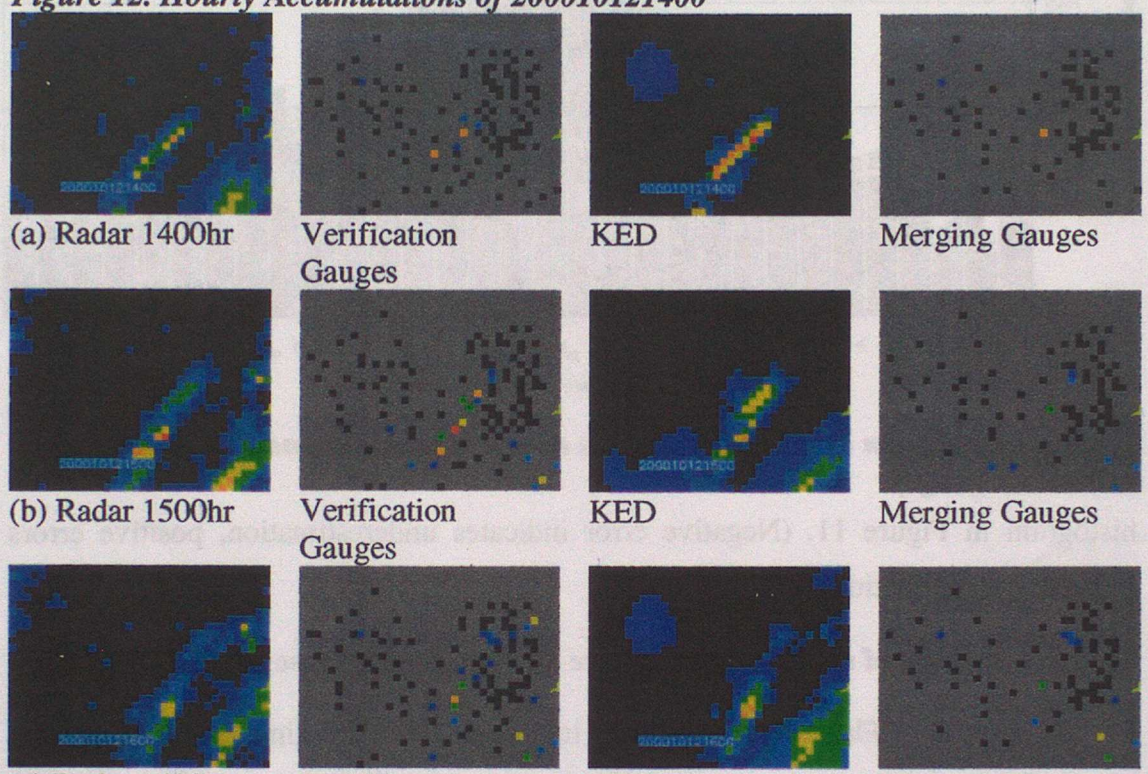
histogram in Figure 11. (Negative error indicates underestimation, positive errors indicate overestimation).

The preservation of small scale structure and localised intense peaks

For the purpose of Flood forecasting it is important that a merging product keeps the structure of small scale localised intense peaks that only the radar captures. The following example illustrates how KED merging behaves in such cases, and how the behaviour depends on the gauge correlation. Figure 12 shows an hourly accumulation sequence from October 12th 2000. In this case, at 1400hrs, a gauge (the merging gauges are shown on the right hand side of Figure 12) catches the edge of the event. Figure 13(a) shows the correlation of the rainfall as a function of distance between the gauges. The correlation length of the rain gauges is of the order of 3-4 pixels. As a result, the contribution of the nearby rain gauges falls off rapidly, leaving the field to be estimated by linear extrapolation from the radar, and thus maintains the small rainfall structure. This would happen when the rain gauges have a low correlation length, even when the rain gauges do not even see part of the rainfall structure (as seen in Figure 13(b) and (c).

Another case to be highlighted is when all the gauges register zero rainfall. In this case, the rain-gauge data will be perfectly correlated. As a result, the rainfall estimation will be zero at all pixel points. Thus any isolated shower, where the rain gauges are perfectly correlated observing no rain will reduced the effect of the radar. There are no examples of this type of event in the Oct -Nov period for localised intense showers.

Figure 12. Hourly Accumulations of 200010121400

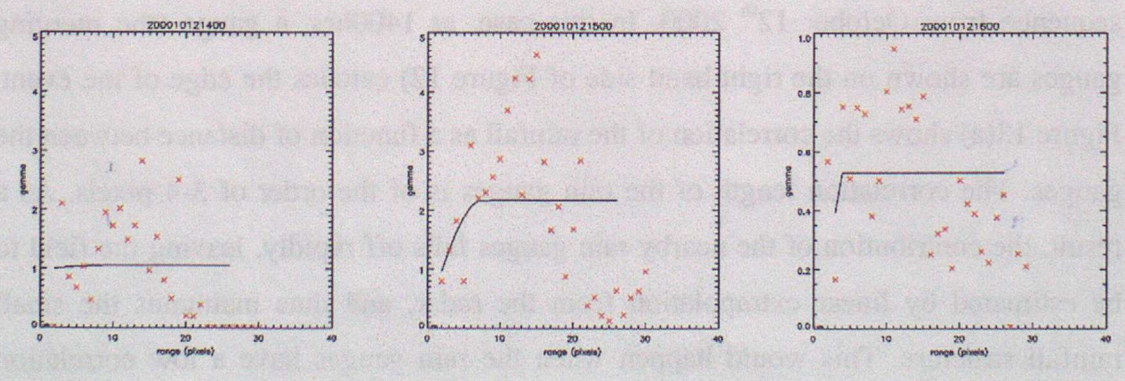


(a) Radar 1400hr | Verification Gauges | KED | Merging Gauges

(b) Radar 1500hr | Verification Gauges | KED | Merging Gauges

(c) Radar 1600hr | Verification Gauges | KED | Merging Gauges

Figure 13. Gauge correlation (variogram) and model for 200010121400-1600



(a) 1400hrs ***(b) 1500hrs*** ***(c)1600hrs***

Product Subjective Quality

An important aspect of any operational meteorological product is that to the customers eye the results are believable. In a case where a customer may be viewing the hourly accumulations as a sequence of events, the case may arise where the merging procedure changes the radar rainfall in a very different way from the previous accumulation field. The sequences of events shown in Figures 5, 6 and 12 show that hour to hour the merging fields look consistent.

The effect of the density of gauges

In order to assess the effect of a decreased gauge density on the results, the experiment was repeated for a gauge density of 1:600km^2, which is slightly lower than the average gauge density expected from the RCP project. The bias, rms and rmsf are shown below. The bias, and rms are similar for both densities, with the higher density showing slightly worse bias and rms than the lower density. This is in contrast to what is intuitively expected, and as the numbers are so similar is thought to be due to the different numbers of events that have been used in each experiment. The

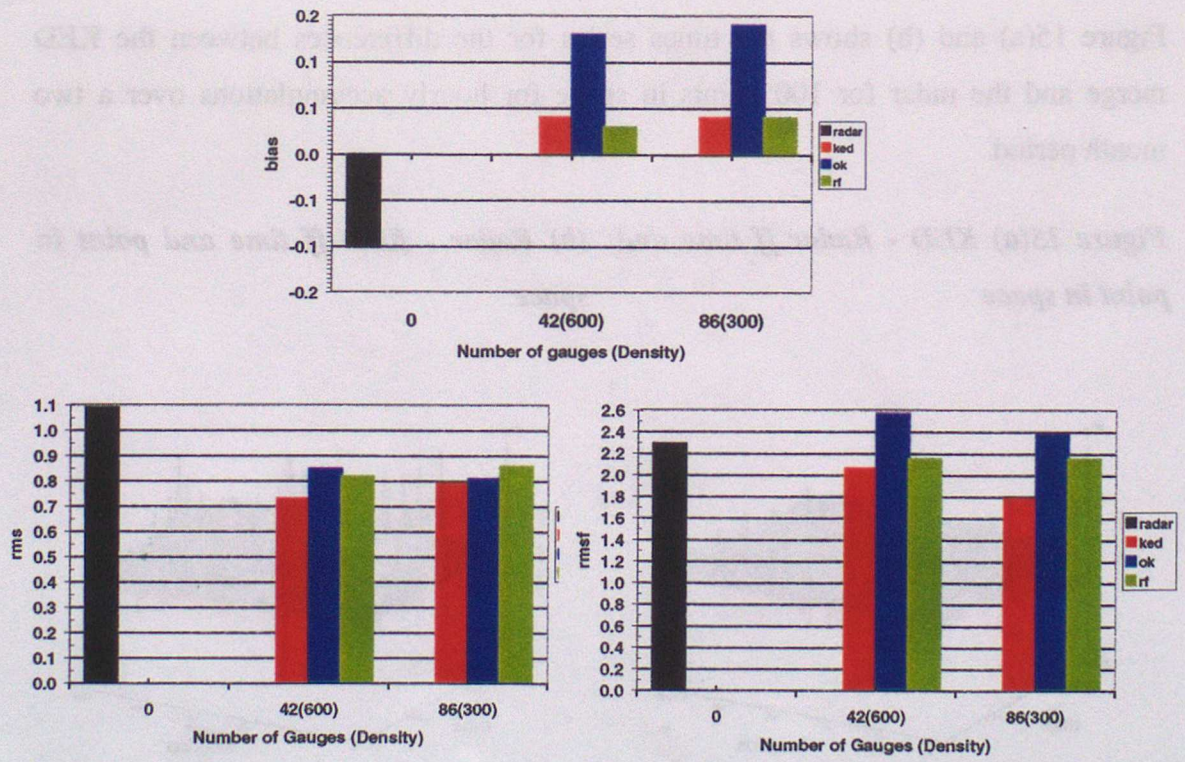


Figure 14. The average bias, rms and rmsf for different numbers of gauges in the EA-Thames region and the corresponding gauge densities.

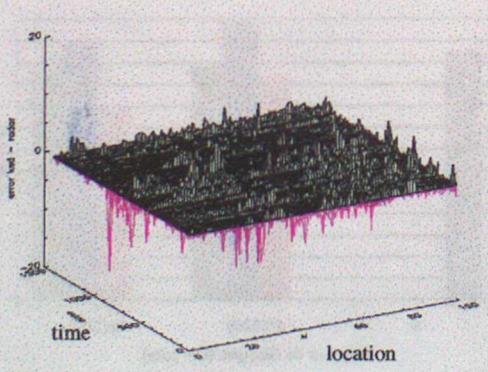
rmsf shows a much clearer trend with a significant reduction in rmsf of the KED and OK schemes, but with little change for the RF method. Lower gauge densities were not explored due to the need to determine the gauge rainfall correlation. For this study is was decided that gauge numbers of less than 40 gave too few pairs, especially at the extreme distances, to determine the rainfall correlation.

The relatively little change in the statistics with increasing density could be an indicator of the error structure of the radar. As the density of the gauges decreases from 300km^{-2} to 600km^{-2}, the average distance to the nearest gauge increases from 3 (15km) pixels to 5 pixels (25km) and therefore it is possible to say that the radar spatial error structure must be correlated over 25 km^2.

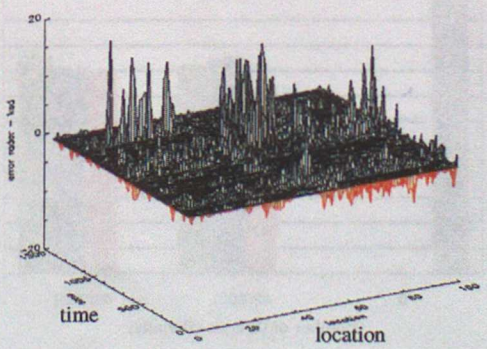
In order to consider how the error structure of the radar changes with time, and thus determine if it would be possible to develop some prognostic adjustment scheme, based on the KED merging fields, for sub-hourly accumulations, a time-series of the difference between the radar and the KED merged accumulations was calculated for 100 points across the grid surface. From this the time correlation of the difference between the radar and Ked accumulations was calculated.

Figure 15(a) and (b) shows the times series for the differences between the KED merge and the radar for 100 points in space for hourly accumulations over a two month period

Figure 15(a) KED - Radar ff time and point in space



(b) Radar - KED ff time and point in space



The time correlation was calculated using the following:

$$\varepsilon_{it} = Ked_{i,t} - Radar_{i,t} \qquad 1.$$

$$\text{mean at time } t = \langle \varepsilon_t \rangle = \frac{1}{N}\sum_{i=1}^{N} \varepsilon_{i,t} \qquad 2.$$

$$\sigma_t^2 = \frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\left(\varepsilon_{i,t} - \langle \varepsilon_t \rangle\right)^2 \qquad 3.$$

$$corr = \frac{\frac{1}{NT}\sum_{i=1}^{N}\sum_{t=1}^{T}\left(\varepsilon_{i,t} - \langle \varepsilon_t \rangle\right)\left(\varepsilon_{i,t+\delta} - \langle \varepsilon_{t+\delta} \rangle\right)}{\sigma_{i,t}\sigma_{i,t+1}} \qquad 4$$

. where σ^2 is the variance of ε in time. *Corr* is the correlation in time over a time δ=*1,2,3,4,5hours*. *i=1,2,....,100* are the number of points in space and *t=1h,2h.....1000h*, the 1000 sequential hourly accumulation points in time

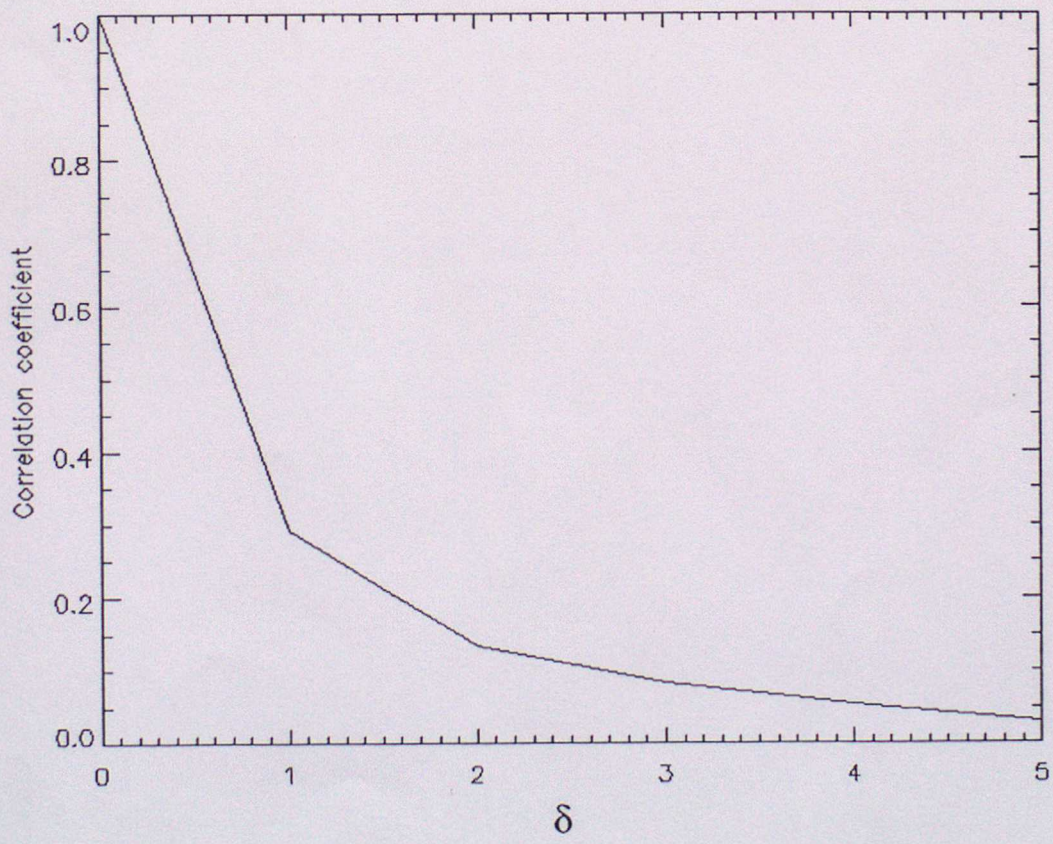
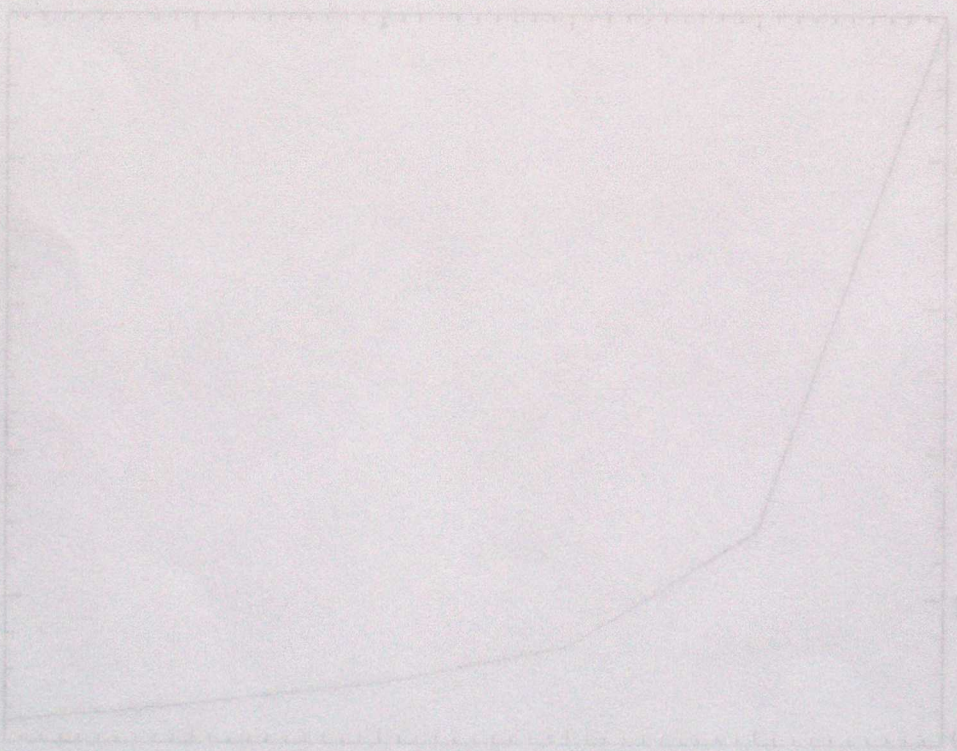


Figure 16 The correlation of KED - Radar at time (t) and KED-Radar at time t+δ for increasing time difference

The correlation was calculated for differences in time of up to 6 hours. Figure 16 shows that the correlation of the difference in Ked and Radar accumulations between one hour and the next is around 30%. This shows that the changes the application of KED makes to the radar field are not well correlated from hour to hour. This is an important fact if the KED *merging* scheme was ever going to be used to produce a *Adjustment* scheme to correct radar on sub-hourly time scales. This also illustrates the problems associated with producing an Adjustment scheme to correct real time radar data and the benefits of using a merging schemes.



Conclusions

Radar - rain gauge merging has been investigated for sub-daily accumulation periods using both a deterministic method (the recursive filter) and a statistical method (Kriging with External Drift). The two methods were tested in the EA-Thames region for the two month period October-November 2000 and compared to Nimrod radar accumulations and gauge-only accumulations. Two gauge densities of 1:300-km^2 and 1:600km^2 were tested for each of the merging procedures

The main points are summarised below;

- 6 accumulations periods were tested; 1,2,3,6,12 and 24 hours
- 2 gauge densities were investigated 1:300km^2 and 1:600km^2
- The correlation of the rainfall was determined by minimising a spherical covariogram function to the data for each accumulation event. The merging techniques were not investigated for a gauge density of less than 1:600km^2 to difficulties in calculating the rainfall correlation for small numbers of gauge pairs
- Radar accumulations, on average overestimated the rainfall, gauge only accumulations, on average underestimated the rainfall
- Below three hours, the gauge only accumulations showed large increase in bias, rms and rmsf relative to the Radar only accumulations
- The statistical KED method exhibits on average the lowest rms and rmsf, improving on rmsf radar values by 22%, and the rms values by 27% for accumulations periods of 1 hour. These improvements were in addition to the improvements made by nimrod to the raw radar which on average see improvements in rmsf of 17%.
- The KED method improved on the radar accumulations 91% of the time
- The deterministic RF method did not significantly reduce the rmsf values compared to the radar or the gauge - only accumulations

- Below three hours accumulation time, the errors due to gauge quantisation representativeness increase, however significant benefits were still obtained using the KED method compared to radar alone.

- Overall, the critical success index (CSI) for rainfall detection improved from 0.44 for the radar to 0.64 for the KED analysis, notably the KED method was improving on the FAR.

- A small number of events were found to have negatively influenced the radar statistics. Notably, there was evidence that bright band effects had contributed to the severe overestimation of rainfall.

- The decrease in gauge density from 1:300km^2 - corresponding to 500 gauges in England and Wales - to 1:600km^2 - corresponding to 250 gauges in England and Wales - did not significantly reduce the benefits of the KED merging schemes. This suggests that the radar errors are correlated on scales of 5 pixels.

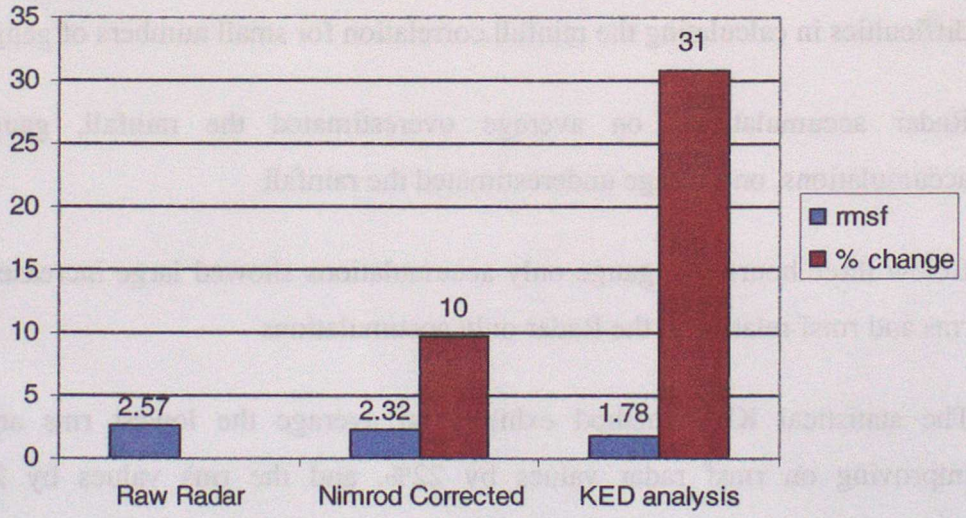


Figure 17. The rmsf of the raw radar, Nimrod corrected radar and the KED analysis for the October-November 2000 period.

Overall, the positive benefits of using the statistical merging technique that were observed for 24 hour accumulations in the first part of this sub-project (September 2001) have been repeated for sub-daily accumulations. The benefits extend to accumulations periods of 1hr with big improvements in bias, rms and rmsf upon radar

accumulations. The relative improvements on average for the trial period for accumulations periods of 1 hour in rmsf are shown in Figure 17.

Recommendations

- Trial of the KED algorithm through the more convective summer months
- Implementation and trial of the KED algorithm to merge hourly accumulations of Nimrod radar data and gauge data at a density not below 1:600km^2 (250 gauges)
- Implementation of the hourly accumulations into the soil moisture scheme

Alice Crossley 2001 10 05

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